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GRS electronics for a space-borne gravitational wave observatory

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Abstract. The Gravitational Reference Sensor (GRS) electronics is a crucial element of the future space-borne gravitational wave observatory. Together with the optical metrology system, it provides position measurements of the sensor's reference body, a Test Mass (TM), for all axes. This is needed for precise spacecraft control. In addition, the GRS electronics can actuate the TM using electrostatic forces, which is used to keep the TM centered in its enclosure or to follow a certain guidance. The GRS electronics has been successfully tested during the LISA Pathfinder mission, launched in December 2015. The electronics has been designed in Switzerland by RUAG and HES-SO under supervision of ETH Zurich and University of Zurich. The paper describes the working principle and the adopted technical solutions for the LISA Pathfinder GRS electronics and for the LISA GRS electronics prototype. Both confirm the readiness of the technology for LISA.

1. GRS Front End Electronics

The Gravitational Reference Sensor (GRS), the associated Front End Electronics (FEE) and the laser metrology system are the core of the future space-borne gravitational wave observatory, the Laser Interferometer Space Antenna (LISA) [1]. To verify the technology readiness for a space-borne gravitational waves observatory, ESA has launched the LISA Pathfinder (LPF) spacecraft in December 2015, which completed its main mission in 2016 and is currently in extended mission phase until May 2017 [2]. The LPF GRS FEE, also called Inertial Sensor FEE (IS FEE), has been designed in Switzerland by RUAG Zurich and HES-SO Sion under supervision of ETH Zurich and University of Zurich.

The FEE, provides position measurements of the GRS's reference body, a Test Mass (TM), for all axes [3]. This is needed for precise drag-free spacecraft control on those axes not controlled by the optical metrology. In addition, the FEE can actuate the TM using electrostatic forces, which is used to keep the TM centered in its enclosure or to follow a certain guidance.

Figure 1 shows simplified block diagram of the FEE and the TM in two Degrees of Freedom (DoF) x and φ, with the remaining DoF omitted for clarity. The TM is electrostatically suspended between surrounding sensing and actuation electrodes and biased by a stable 100 kHz AC signal via separate injection electrodes, i.e. by capacitive coupling. The TM position sensing is based on measurement of capacitances existing between electrodes and TM along all DoF. Its motion causes an imbalance in capacitance, and thus an imbalance in AC currents flowing in primary windings of both transformer bridges (between front/rear electrodes A+/- and B+/-). The preamplifier, following the bridge, detects the differential current in the transformer secondary winding and converts it to an AC voltage, which is then band-pass filtered (BPF), converted into DC voltage by a synchronous demodulator and then finally digitized by an Analog to Digital Converter (ADC).

To allow for a high sensitivity of capacitive measurement, the transformer with a high quality factor Q is operated at a resonance, matching the injection bias frequency, for which capacitors (Cp) are added in parallel with inductance of the primary windings. The sensing noise has its minimum at resonance and needs to be precisely tuned. This tuning capacitance includes the capacitance of the cables, which requires individual tuning of every sensing channel.

In order to reduce the stray acceleration on TM or to add some guidance, force signals are provided by numerically synthesized AC waveforms at audio frequencies (60 – 270 Hz), not to interfere with the sensing circuit operated at 100 kHz. To apply strong forces on TM during its release or spacecraft maneuvers, large AC voltages are needed (120 V) and operated in the Wide-Range (WR) actuation mode. The force signal for each electrode is converted into voltage by a Digital to Analog Converter (DAC) and amplified by a corresponding amplifier. Actuation signal is then filtered and applied on the same electrodes used for sensing, such that actuation and sensing circuits operate simultaneously with minimum crosstalk.

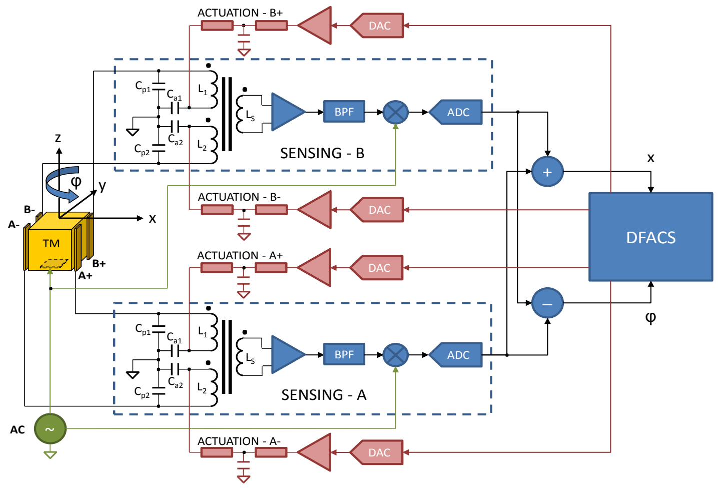

Figure 1. A block diagram of the TM sensing and actuation electronics associated with the x and φ DoF. Two pairs of electrodes (A+/A-, B+/B-) allow simultaneous measurement of TM translation and rotation, which is achieved by measurement of the gaps between TM and electrodes at TM corners. The capacitance is proportional to the respective TM - electrode gap. Actuation circuit (one for each electrode) electrostatically applies forces and torques on TM using same electrodes.

As shown on figure 1, two capacitive measurements are combined to calculate TM translation (x) and rotation (φ). Similarly, other 8 electrodes (not shown for clarity) are used to derive remaining TM motion in y – θ and z – φ DoF. TM attitude and control forces are calculated by the Drag-Free Attitude Control System (DFACS) software located in the LPF spacecraft On-Board Computer (OBC).

2. LISA Pathfinder GRS FEE sensing performance

The sensitivity of the capacitive measurement is limited by the quality factor Q of the differential transformer, whose losses produce thermal noise. To achieve the required sensitivity with the sensing noise density of 1 aF/√Hz (equivalent to 1.8 nm/√Hz), transformer must have large inductance and large Q (> 150) [4]. This requires low inter- and intra-winding stray capacitances. In addition, the challenging requirement of < 50 ppm is needed for inductance imbalance between primary windings to achieve sensing offset better than 600 aF (1 µm) in the ±200 µm High-Resolution (HR) sensing range.

For stability reasons, a planar winding design with balance tuning capability of the two primaries was selected. Each winding is made of 16-layer Printed Circuit Board (PCB). All three windings are glued together and this stack is then precisely positioned and glued against the gap of the Ferrite core. The transformer is designed by Swiss industry (HES-SO Sion). A similar transformer winding design, made by ETH, is shown on figure 2.

Figure 2. An example of the planar differential transformer design, i.e. a stack of two primary windings and one secondary winding separated by Teflon spacers. Each winding has 80 turns, which is constructed by stacking 16 layer coils, each with 5 turns. A gapped Ferrite core surrounds the stack to form the transformer.

Any instability in the sensing bias amplitude (100 kHz injection signal) mimics TM motion and causes low frequency noise proportional to the TM out-off-center position. The amplitude stability of the bias must therefore, be better than 50 ppm/√Hz not to compromise sensing noise performance in the measurement range of interest, i.e. at ±10 µm TM displacement (HR performance range). In LPF, the 50 ppm/√Hz stability requirement is fulfilled at 1 mHz.

Test of sensing performance requires a TM simulator, which is a 6 fF differential capacitance simulator (10 µm equivalent TM displacement) with nominal capacitance in each arm of ~1 pF (equivalent to 4 mm gap between TM and electrode). With the presence of such a low capacitance, the fluctuation of stray capacitances in the simulator can produce low frequency noise and thus mask the true FEE sensing performance. The ground measurements of sensing performance already showed an excess noise at 1 mHz indicating that an improved simulator design is needed for LISA band of 0.1 mHz.

The sensing performance check was performed in flight with TM grabbed by mechanical fingers in z-axis. Figure 3 shows that this provided better differential capacitance stability than the on-ground simulators (note 10 nm equivalent TM drift during 20 hours). Sensing noise performance with TM translated by 2 µm in z-axis was found to be 1.4 nm/√Hz and flat down to 1 mHz.

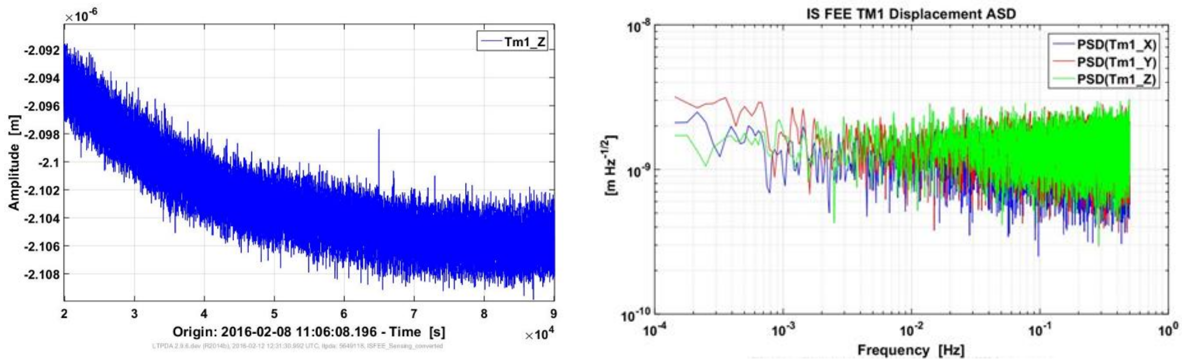

Figure 3. The TM displacement (stability) in z-axis (left) and a corresponding amplitude spectrum density in all three axes (right) measured during GRS FEE commissioning in space.

3. Design Upgrades for LISA

LISA performance in sensing and actuation must extend at least to 0.1 mHz for which some design changes are needed. For non-zero TM displacement the injection bias amplitude stability must improve since the amplitude noise density on LPF FEE is 150 ppm/√Hz at 0.1 mHz. The design improvement of the TM simulator is already mentioned in the text, as a prerequisite for accurate on-ground verification of sensing performance below 1 mHz. Furthermore, the 2 ppm/√Hz actuation amplitude stability has to be achieved at 0.1 mHz since the LPF FEE performance is 4-7 ppm/√Hz at 1 mHz and 12-60 ppm/√Hz at 0.1 mHz.

As the voltage reference circuit is the main performance driver for the amplitude stability of the sensing bias and actuation waveform, the voltage reference circuit has to be modified. Additional modifications are also needed in the actuation electronics where zero-offset (auto-zero) amplifiers and other drift cancelling techniques shall be implemented to reduce the low frequency noise.

A prototype of the LISA GRS FEE has already been manufactured by ETH Zurich, RUAG Zurich and HES-SO Sion. HES-SO designed the sensing and actuation circuits, RUAG the control electronics, box and integrated the unit. ETH designed the Reference Unit with stable voltage reference and performed the performance testing of the integrated electronics. The sensing bias and actuation amplitude stability is already fulfilled for LISA prototype as shown on figure 4 and figure 5.

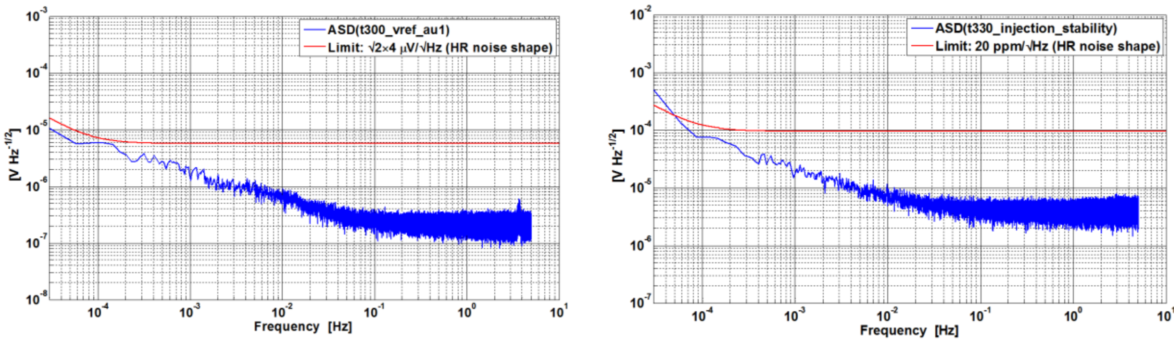

Figure 4. The LISA prototype voltage reference amplitude (left) and sensing bias, 100 kHz amplitude (right) stability spectrum densities. The voltage reference stability limit is equivalent to √2 x 1.6 ppm/√Hz for the 2.5 V reference. The sensing bias stability was measured at nominal 4.83 V level.

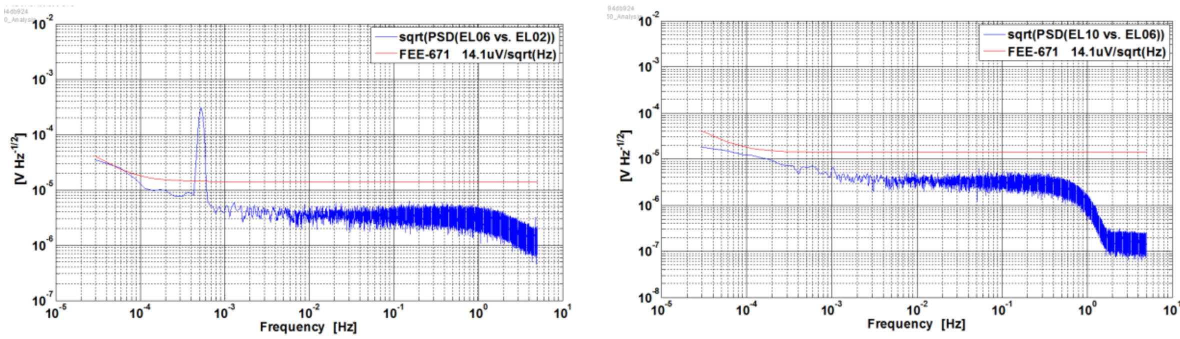

Figure 5. The LISA prototype actuation in-band DC noise (left) and 120 Hz actuation waveform amplitude stability (right) spectrum densities. The actuation DC noise limit is set to √2 x 10 μm/√Hz and measurement is performed at 5 V DC and 5 V AC simultaneous actuation. The actuation waveform amplitude stability limit is equivalent to √2 x 2 ppm/√Hz for the 5 V AC actuation.

For the voltage reference and the actuation noise / stability testing a differential measurement technique was used for which noise limits were multiplied by factor √2. The voltage reference and actuation DC noise test used uncorrelated voltage reference circuits. The phase of two actuation waveforms in differential measurement setup could not be perfectly equalized, which generated an aliasing peak in the DC noise plot. This was a measurement artifact, which does not affect the true performance. The differential actuation stability test (right trace on figure 5) required a locking amplifier with tuned amplitudes of two waveforms with small residual differential input. A single reference circuit was used, with the consequence that the correlated reference noise was removed from measurement, thus leaving only the uncorrelated noise sources. In real operation, the correlated noise will be cancelled as well since a common voltage reference will be used on all actuation channels.

4. Conclusion

GRS FEE technology was tested during LPF main mission phase and the required performance has been achieved in 1 mHz frequency bandwidth, as set for LPF. The requirements for a space-borne gravitational waves observatory are more stringent and extend at least to 0.1 mHz for which a LISA GRS FEE prototype has been developed and tested in Switzerland. The major modification is the design of a single voltage reference unit common for all DoF, compared to a LPF design with distributed reference for each quadruple of electrodes. The voltage reference, stable to 2 ppm/√Hz at 0.1 mHz is a prerequisite for the GRS performance. This level of performance has been achieved and it is essential for the performance of the sensing and actuation circuits that rely on voltage reference. The sensing and actuation noise performance has been verified down to 0.1 mHz.

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